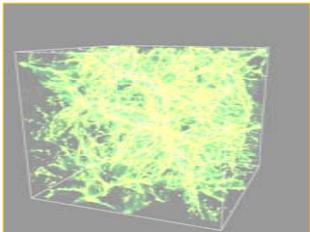


Constellation-X and the Missing Baryons

Fabrizio Nicastro (CfA)

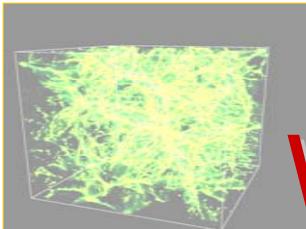
Smita Mathur (OSU), Rik Williams (OSU), Martin Elvis (CfA), Nancy Brickhouse (CfA), Fabrizio Fiore (OAR-INAF), Yair Krongold (IA-UNAM)



Why Should we Care?

(54 ± 9) % of Baryons are missing!

- Find the 'Missing Baryons' and verify theory
- Ecology of the Universe (Metal Pollution)
 - Absolute (**needs UV**) and Relative Metallicities.
 - Galaxy Superwinds (SN) vs AGN winds, jets
 - Nucleosynthesis
- Heating History of the Universe
- Cosmological parameters from density fluctuations of WHIM filaments (1-10 Mpc at $z=0-2$): > **10³ systems needed**
 - LG-WHIM is a biased measure - Need $z>0$ WHIM absorbers to measure Ω_b
- Local Group WHIM and Galaxy formation

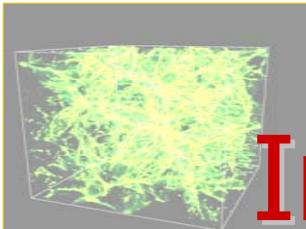


WHIM Filaments are Faint

- **Size:** $\Delta R \sim 1 \text{ Mpc}$
- **Density:** $n_b \sim 10^{-6} - 10^{-5} \text{ cm}^{-3}$
- **Temperature:** $T \sim 10^6 \text{ K}$; $\xi_{\text{OVII}} \sim 1$
- **Metallicity:** $Z \sim 0.1 Z_\odot$

=> **OVII-Forest Column Density:**

$$N_{\text{OVII}} \sim n_b \xi_{\text{OVII}} Z_\odot \Delta R \sim 2.6 \times (10^{14} - 10^{15}) \text{ cm}^{-2}$$



Instrumental Requirements

$$W_{OVII} \approx 3 \times 10^{-18} (1+z)^2 N_{OVII} \approx 0.8 - 8 (1+z)^2 \text{ m}\overset{\circ}{\text{\AA}}$$

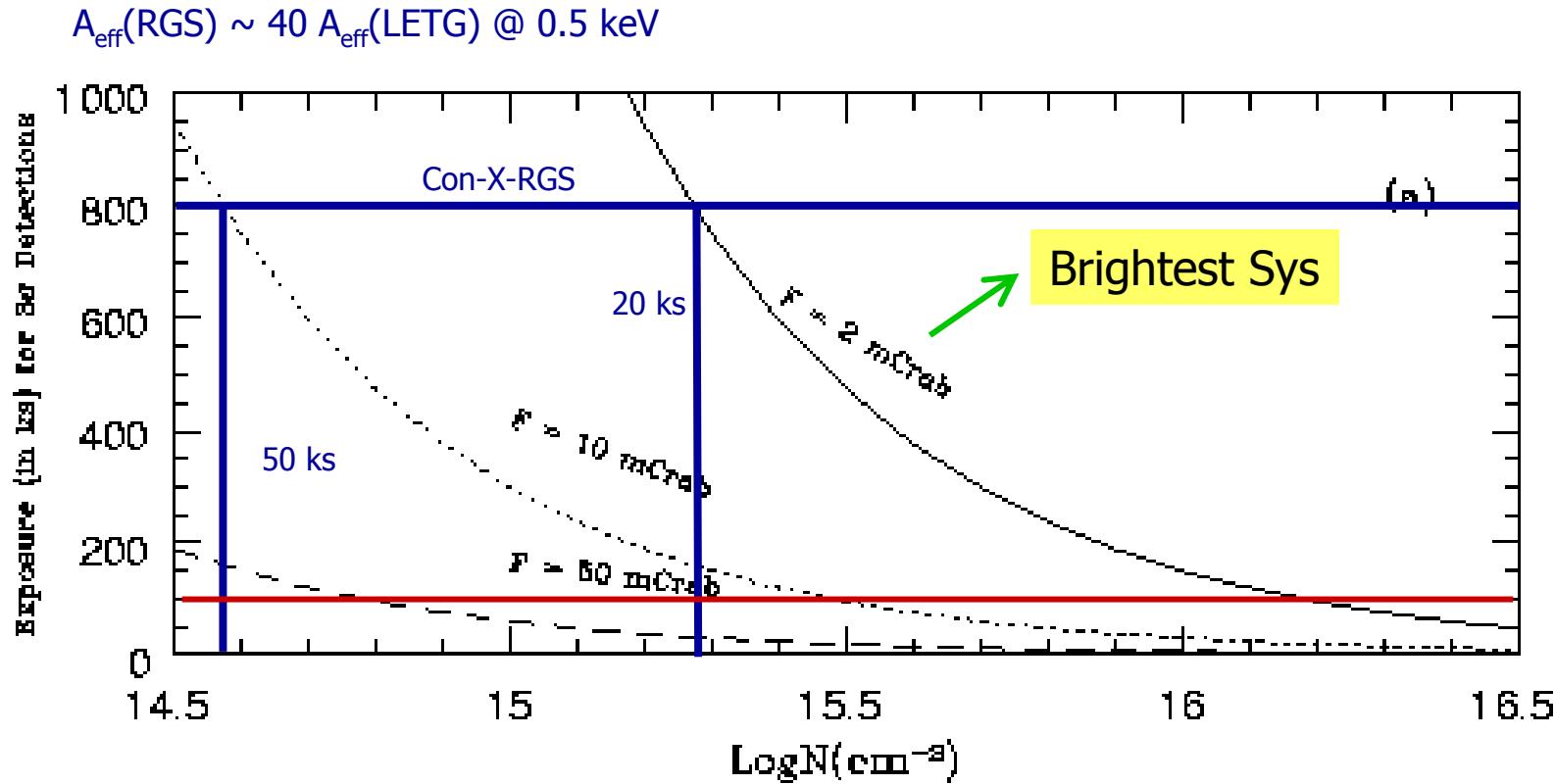
$$W_{N_\sigma}^{thresh} = N_\sigma \frac{\Delta\lambda}{\sqrt{CPRE}}$$

Resolution → $\Delta\lambda$

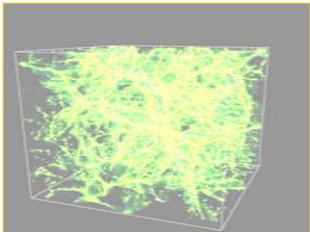
(Eff. Area * Res.)^{0.5} → N_σ , \sqrt{CPRE}

$$N_{OVII}^{Thres} \approx 2.3 \times 10^{15} \left(\frac{N_\sigma}{3} \right) \left(\frac{\Delta\lambda(\text{m}\overset{\circ}{\text{\AA}})}{50} \right) \sqrt{\frac{500}{CPRE}} (1+z)^{-2}$$

Required Exposure with Current Spectrometers... and Con-X-RGS



- **Exceptionally high quality** X-ray spectra of background AGN are needed.



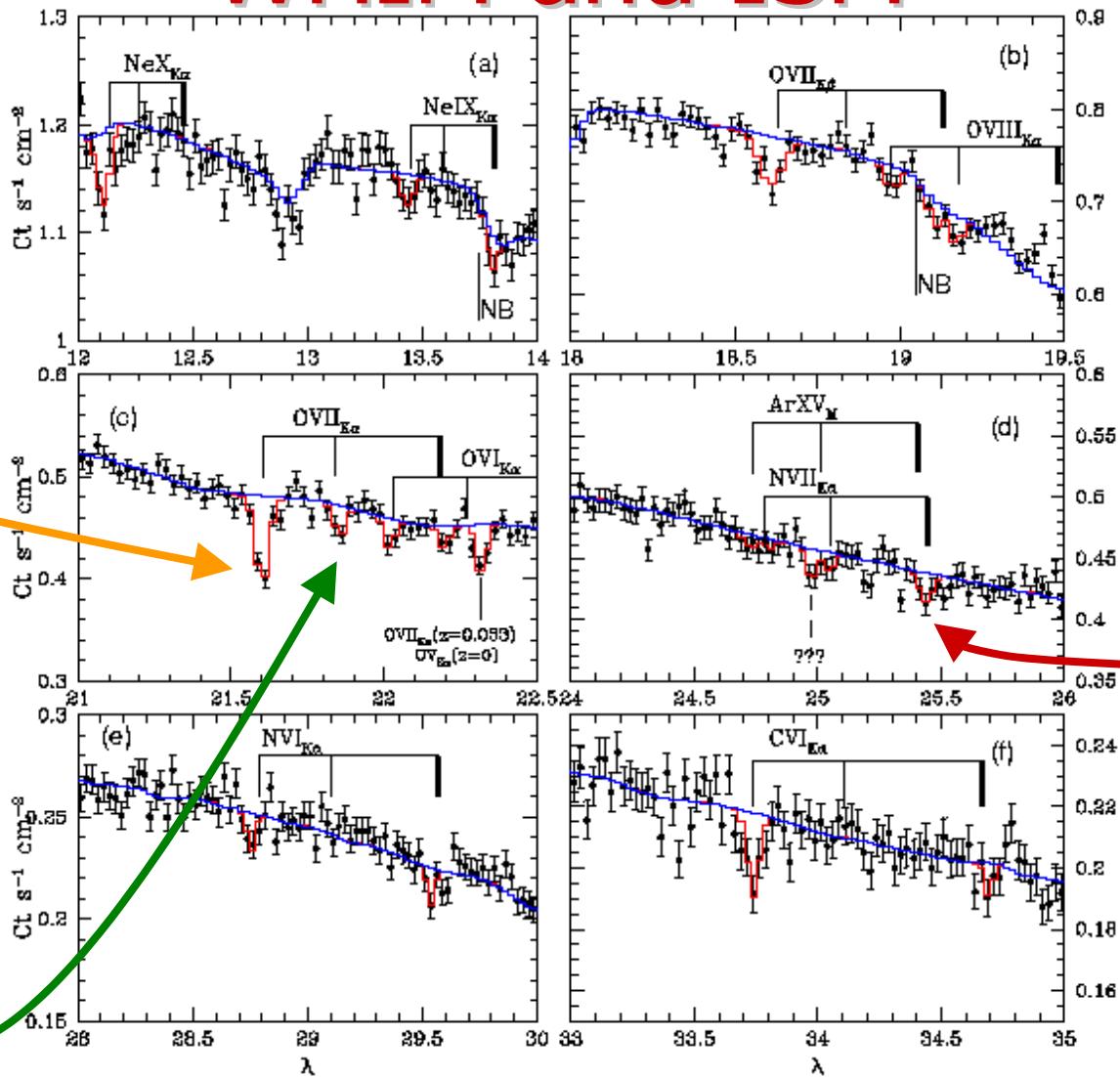
Mkn 421 ($z=0.03$): WHIM and ISM

Chandra TOOs:
6000 CPREs

Local Group
WHIM?

$\langle z \rangle = 0.011$
WHIM

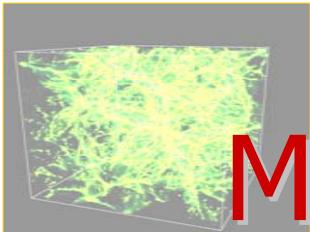
$\langle z \rangle = 0.027$
WHIM



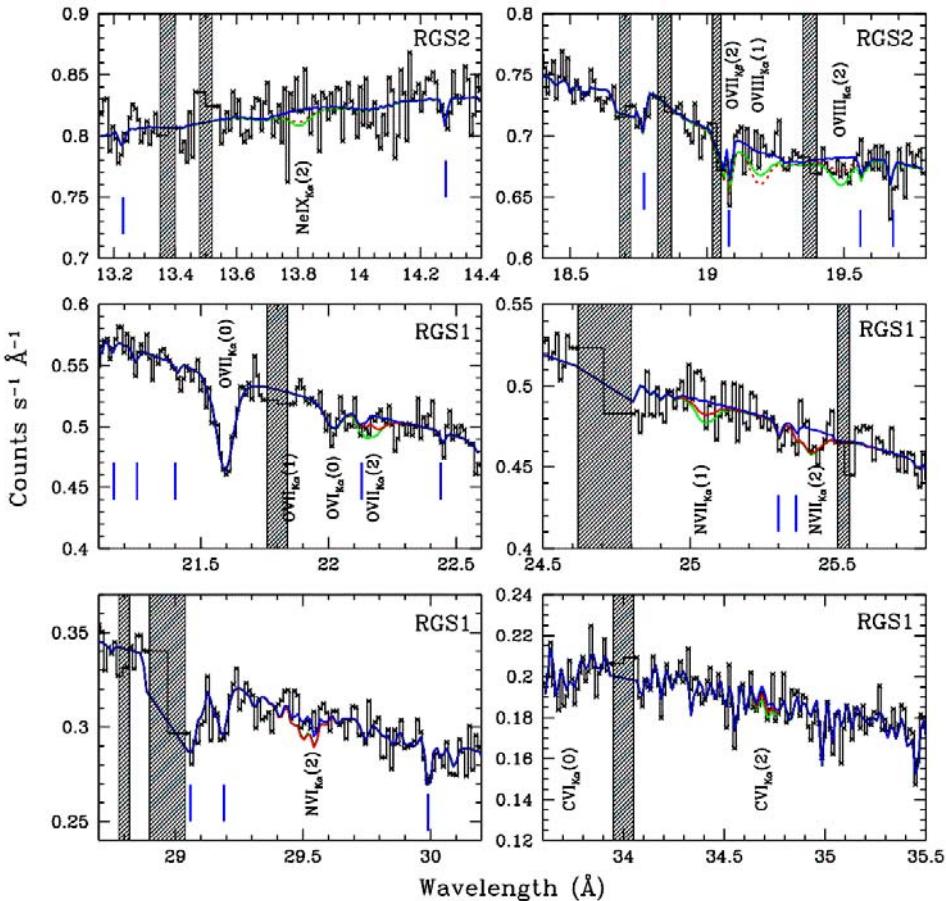
(Nicastro et al., 2005, Nature, 433, 495; Nicastro et al., 2005, ApJ; Williams et al., 2005, ApJ, in press)

2/28/2006

Constellation-X FST (Cambridge, MA; F. Nicastro)



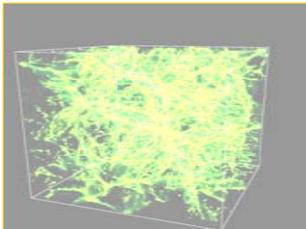
Mkn 421: XMM-Newton-RGS



15000 CPREs! $\sim 2.5 \times$ LETG

1. 20-60 % of Δz blocked by instrumental features
2. Resolution $> 2 \times$ poorer in the line wings
3. Fixed-pattern noise at $\lambda > 29 \text{\AA}$

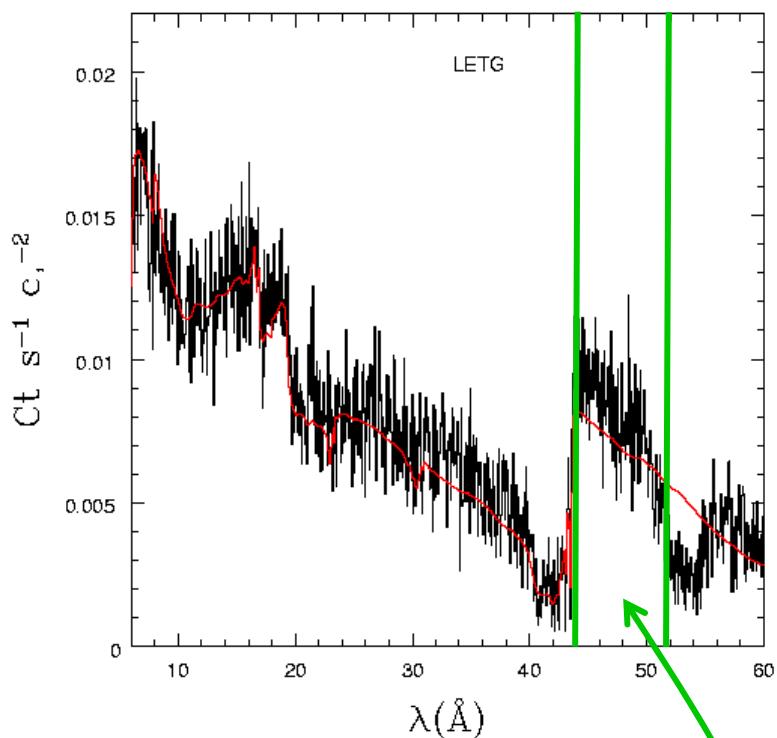
(Williams, Mathur, Nicastro & Elvis, 2006, ApJ, submitted)



1ES 1028+511 ($z=0.361$)

Chandra-LETG: 149 ks

$$F_{0.3-2} = 0.8 \text{ mCrab}$$



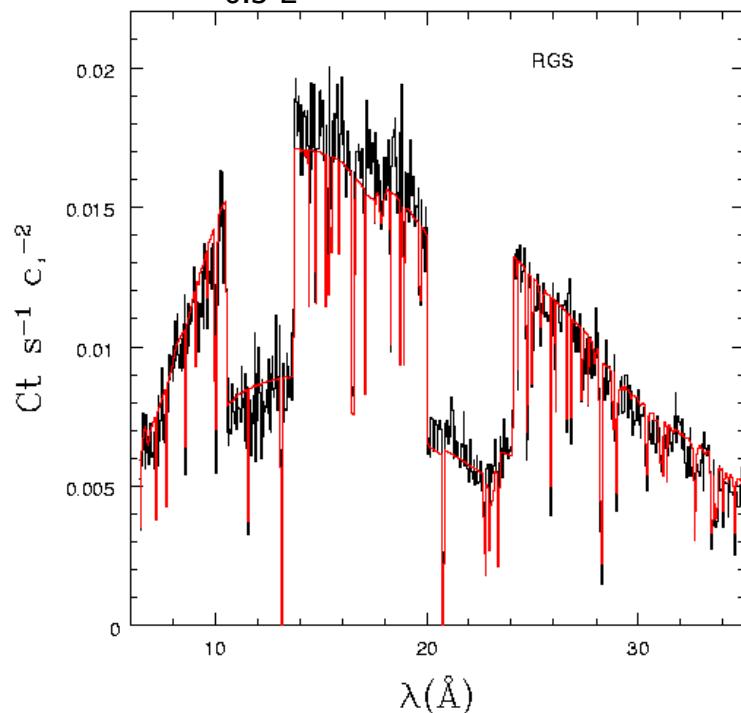
Sensitive to CV-Forest:

$$\lambda \sim 44-52 \Rightarrow \Delta z = 0.2$$

$$CPRE(20-30; 44-52) = 60$$

XMM-Newton RGS: 195 ks

$$F_{0.3-2} = 0.5 \text{ mCrab}$$

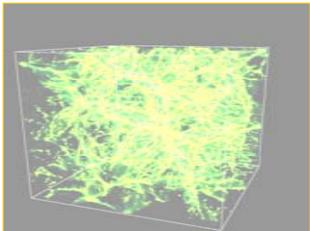


18 % of $\Delta z(\text{OVII})$ is blocked

Left-right contiguous resolution elements

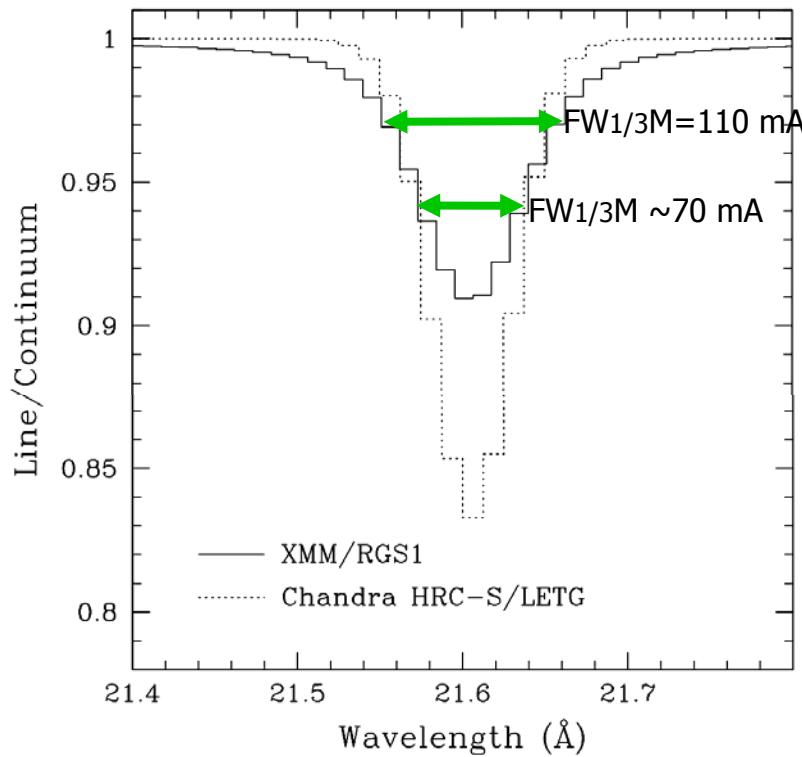
Adds up to $\sim 60\%$ blocking factor!

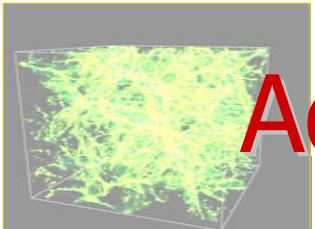
$$CPRE(20-24; 30-36) = 45; CPRE(24-30) = 75$$



LETG & RGS Resolutions

$$R_{\text{core}}(\text{RGS}) \sim R_{\text{core}}(\text{LETG}) = 50 \text{ mA}$$
$$R_{\text{wings}}(\text{RGS}) \sim 2 R_{\text{wings}}(\text{LETG}) = 140 \text{ mA}$$





Advantage of long-wavelength coverage

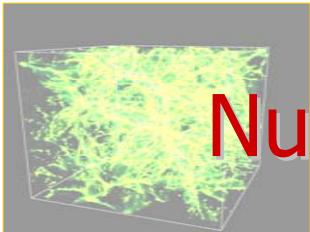
$$N_{He-like}^{Thres} \approx 1.1 \times 10^{18} \left(\frac{N_\sigma}{3} \right) \left(\frac{\Delta\lambda(\text{m}\text{\AA})}{50} \right) \sqrt{\frac{500}{CPRE}} \lambda^{-2}$$

$$\Rightarrow N_{\text{CVI}} / N_{\text{OVII}} \sim 3.5$$

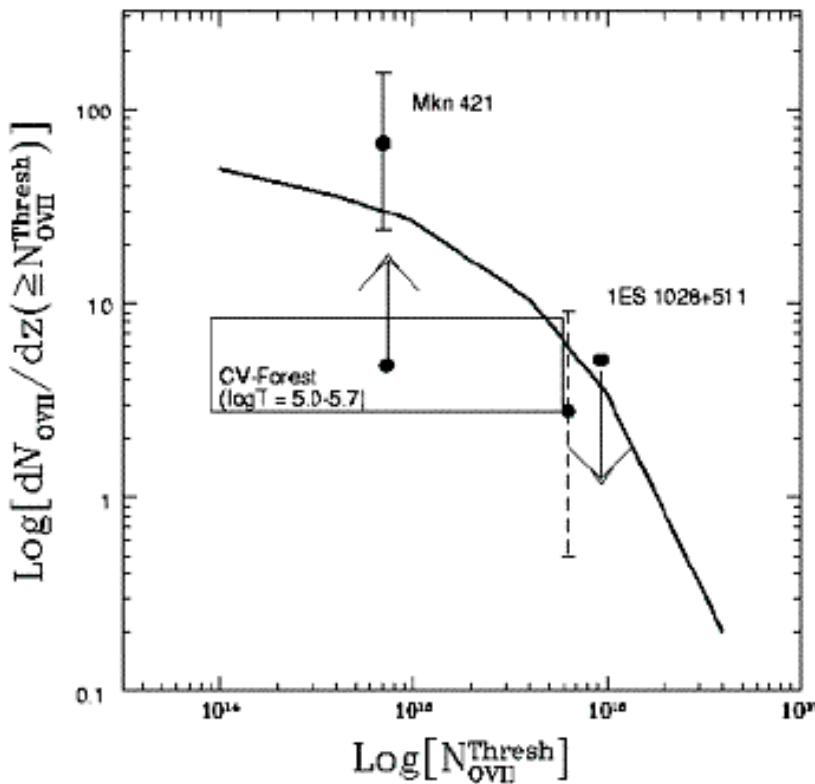
$$N_{\text{OVII}}^{2\sigma} > (5.0 - 9.3) \times 10^{15} \text{ cm}^{-2} \quad N_{\text{CV}}^{2\sigma} > (1.6 - 2.9) \times 10^{15} \text{ cm}^{-2}$$

LETG & RGS Spectra

LETG Spectrum only



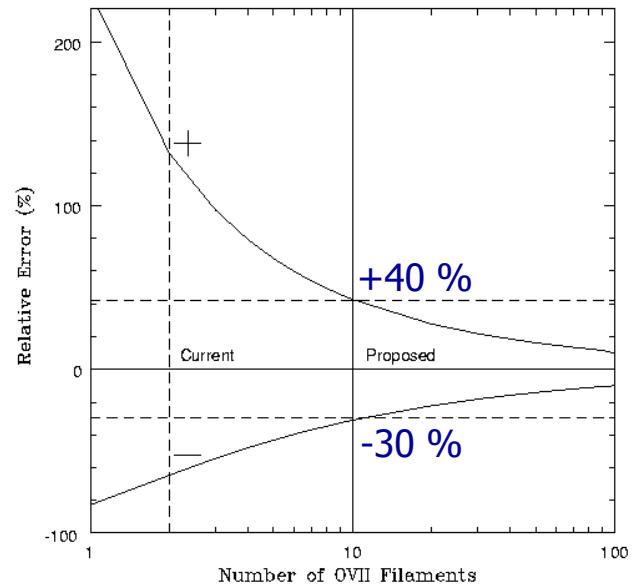
Number Density and Cosmological Mass Density of WHIM



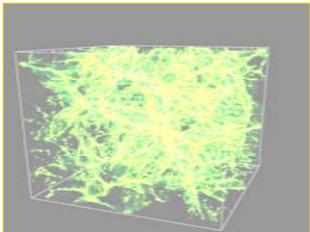
$$\Omega_b(N_{\text{OVII}} > 7 * 10^{14}) = \left(\frac{1}{\rho_c} \right) \left(\frac{\mu m_p \sum N_H^i}{d_{\text{Mkn 421}} + d_{\text{1ES1028+511}}} \right) = 2.4_{-1.1}^{+1.9} * 10^{-[O/H]_1} \%$$

Consistent with $\Omega^{\text{missing}} = 2.5 \pm 0.4$

Short-term Prospects



(Nicastro et al., 2005, Nature, 433, 495; Nicastro et al., 2006, in prep.)



Long-Term Prospects

- Long Term: mapping the WHIM up to $z \sim 1$: needs high throughput and spectral resolution.
- Tens to hundreds systems would enable:
 - Ω_b (R) and dN/dz to better than few/tens %
 - WHIM density in galaxy voids vs galaxy overdensities
 - Multi-phase studies (R) (R) (R)
- Hundreds to Thousands of Systems would enable:
 - Ω_b (R) and dN/dz to better than few tenth of %
 - Cosmological Parameters (density fluctuations)
 - Dark-Matter Maps
 - Metallicity History: dZ/dz (Ecology of the Universe) (needs UV) (R)
 - IGM/galaxy/AGN Feedback
 - Heating History of the Universe (dT/dz) (R)

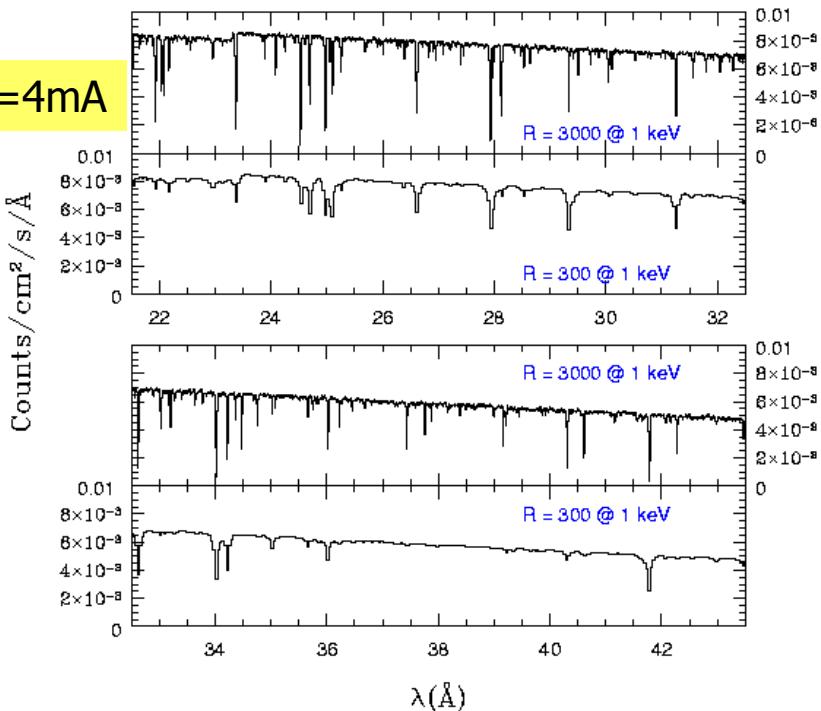
Con-X & the WHIM: Detectability

High Spectral Resolution & Low-Energy Coverage

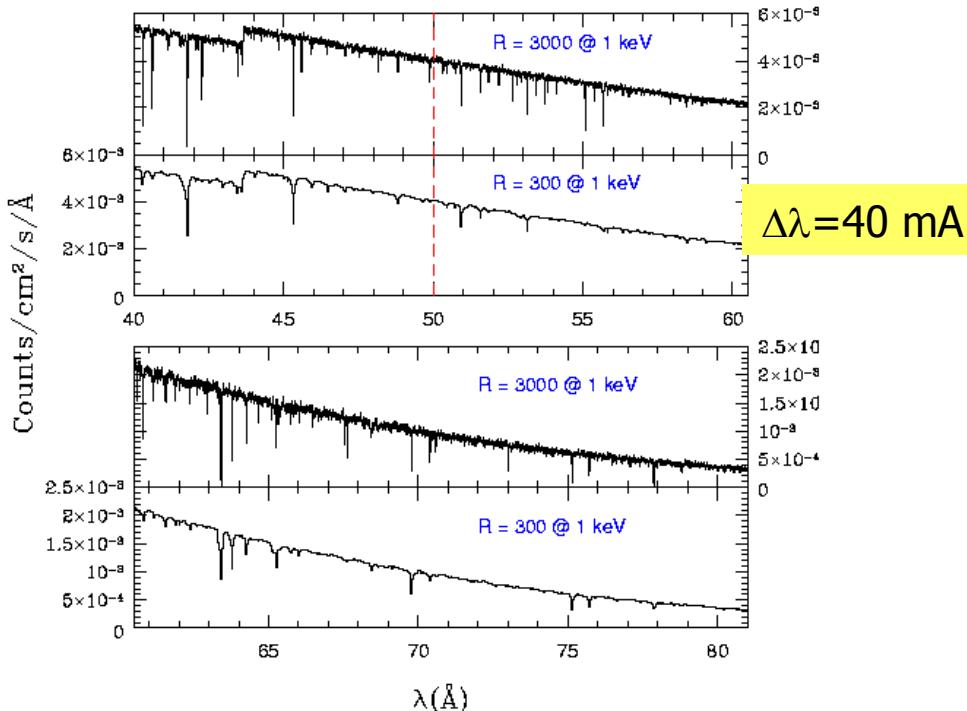
From $z \sim 0$ $dN/dz dN_{\text{OVII}}$ (Fang et al., 2002) extrapolating to $z=1 \implies 48$ systems

$\text{Exp} = 1.5 \text{ Ms}$; $F_{0.5-2} = 1 \text{ mCrab}$

OVII-Forest

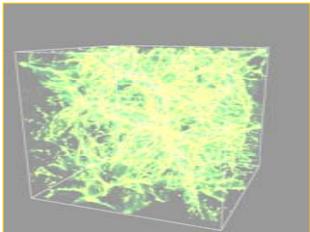


CV-Forest



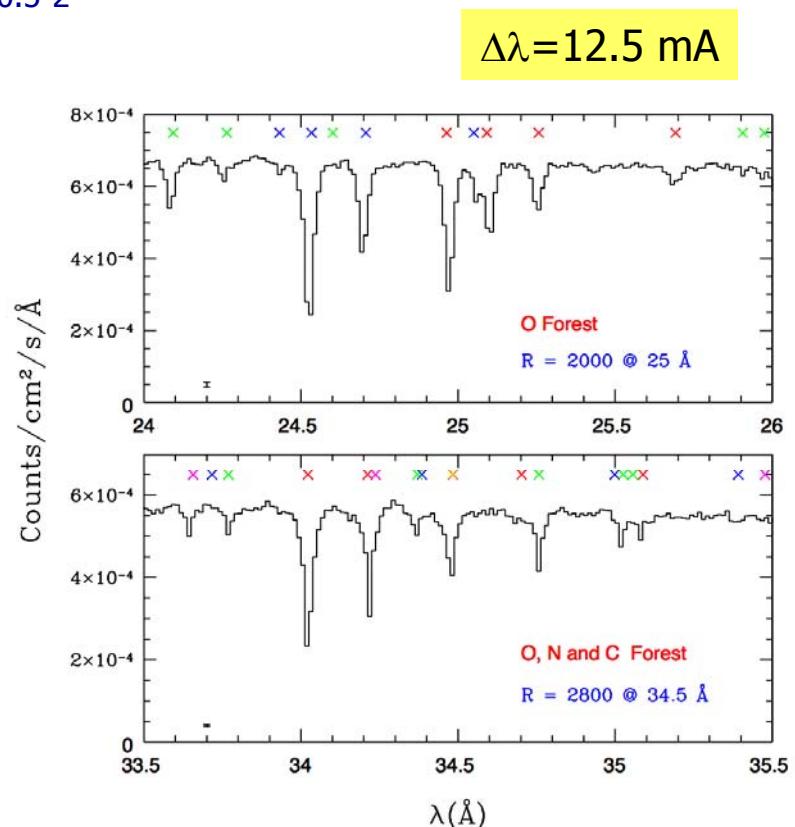
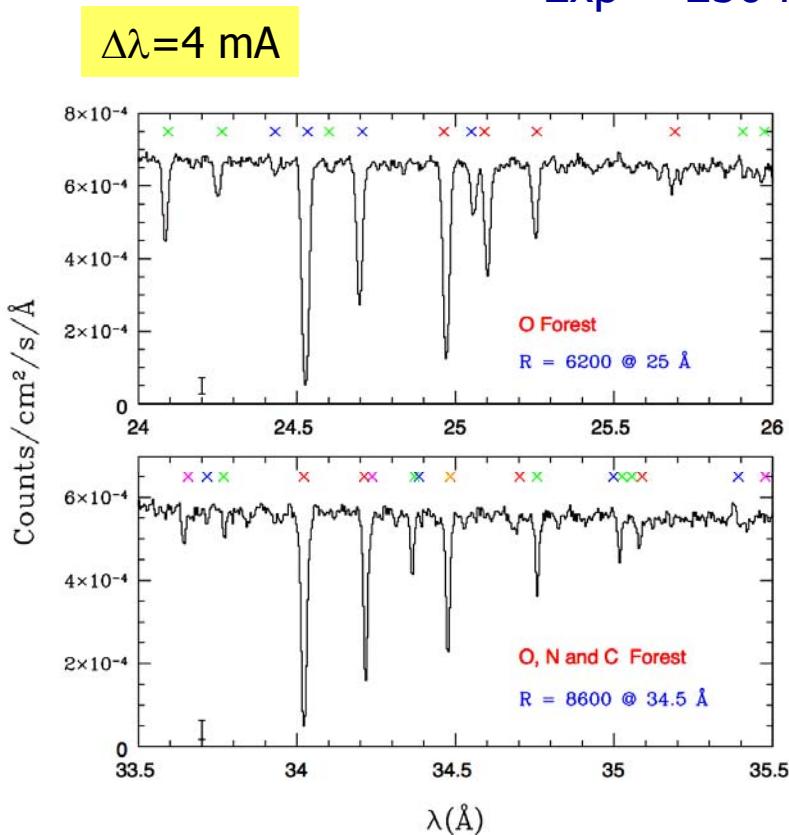
$R = 300 @ 0.6 \text{ keV} \iff \Delta\lambda = 70 \text{ mA}$

[Ideal Gaussian LSF]

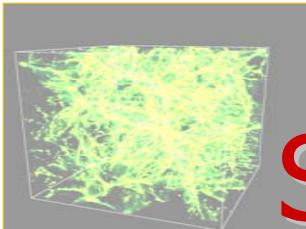


Detectability

Exp = 250 ks; $F_{0.5-2} = 1 \text{ mCrab}$

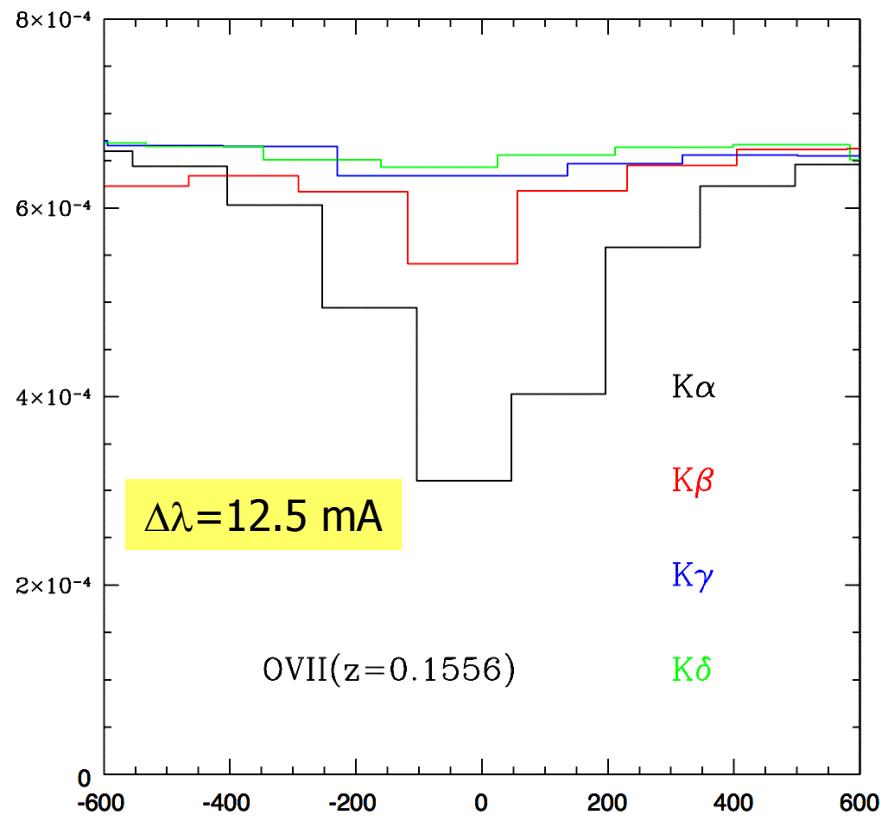
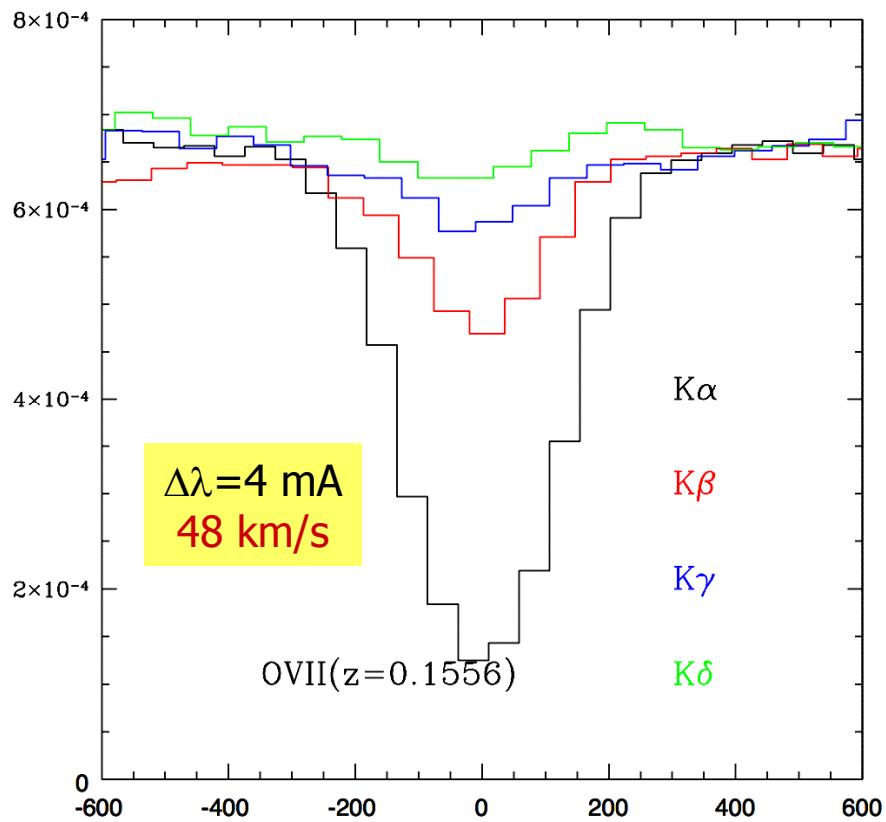


R>1000 at 12 Å guarantees detection of > 80 % OVII systems

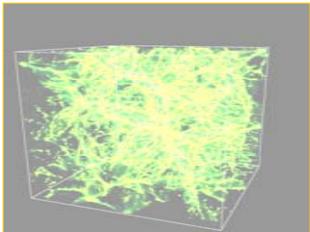


Saturated lines: b and N_{ion}

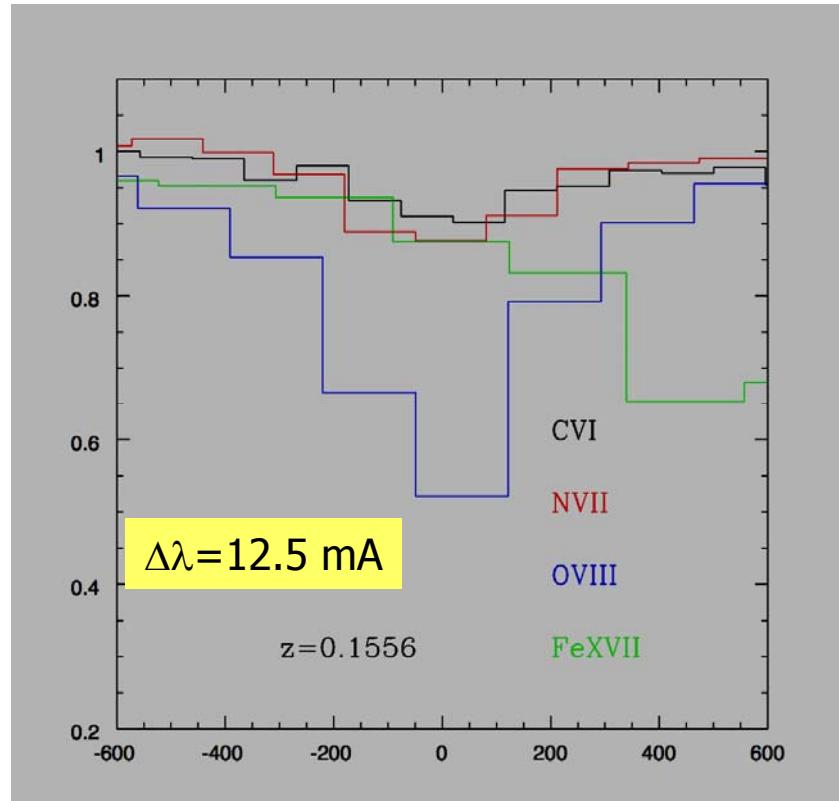
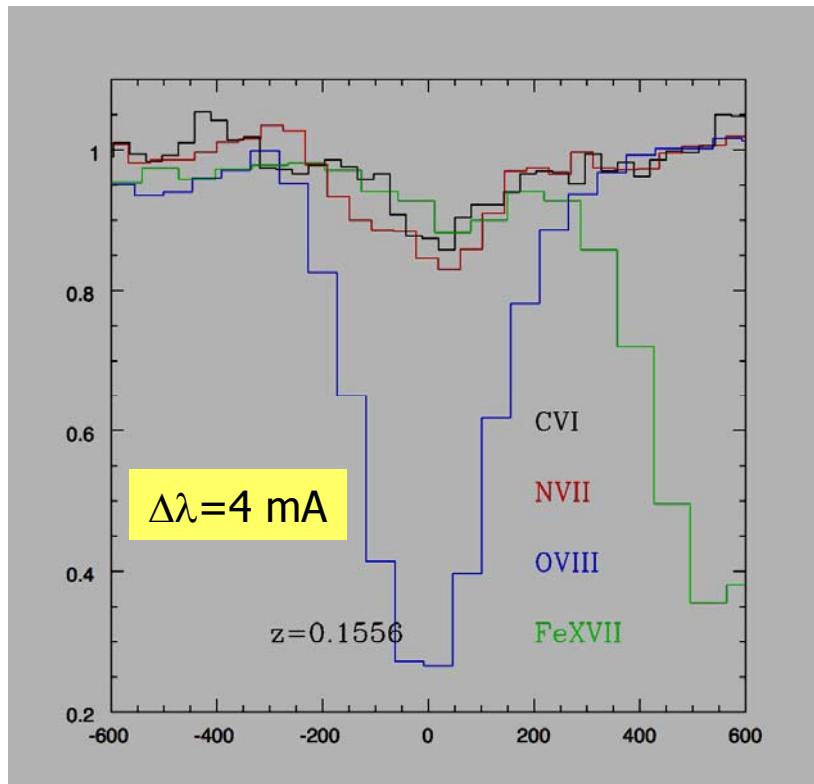
$$N_{OVII} = 5 \times 10^{15}; b = [(b_{therm})^2 + (b_{turb})^2]^{0.5} = 48 \text{ km/s}$$



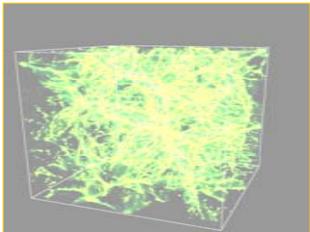
R=1000 at 12 A allows N_{ion} -b decoupling only for brightest OVII systems
Higher R needed!



Relative Metallicity

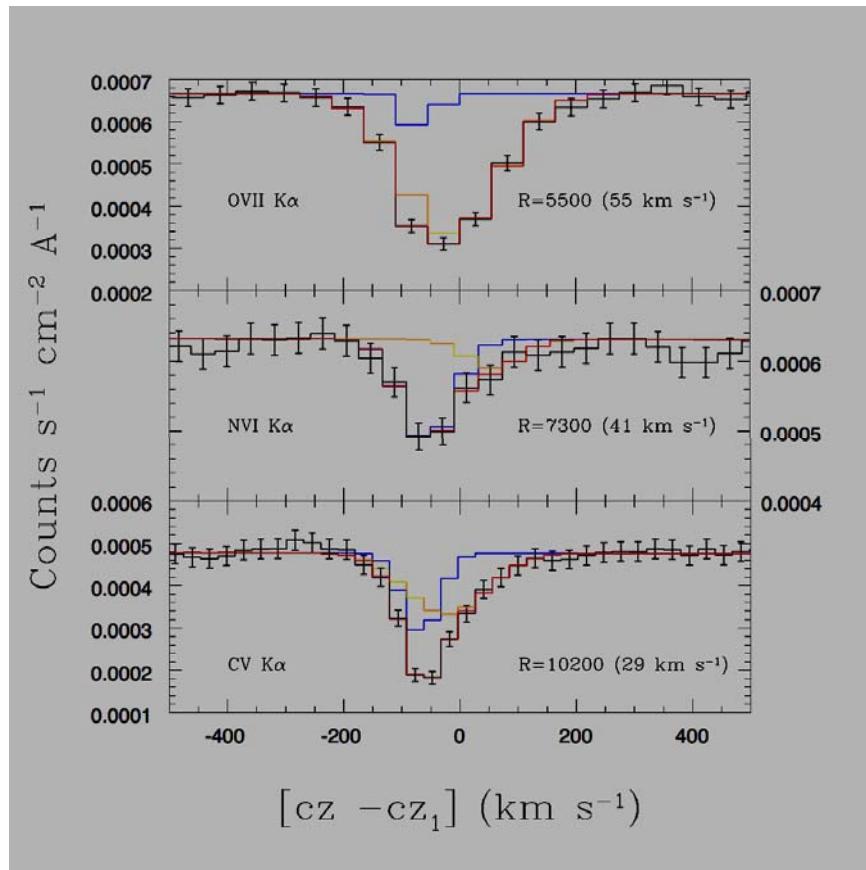


Needs R > 3000 at 12.4 Å



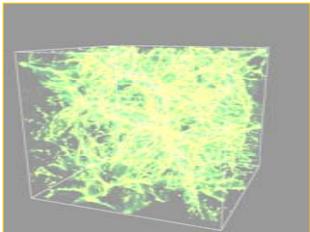
Multiphase WHIM

$\Delta\lambda=4$ mA



2 WHIM phase in pressure eq.
Total extension 2.2 Mpc along the
line of sight

Start to be resolved at R>3000 at
1 keV



Conclusions

- $A=1500 \text{ cm}^2 R=200 @ 1 \text{ keV}$ (**Con-X baseline**):
 - detects tens OVII systems along 2 dozens of low-z sightlines ($F_{0.5-2} > 1 \text{ mCrab}$)
 - Measures $dN/dzdN_{\text{OVII}}$ and Ω_b at better than 30-40 % (but Ω_b depends critically on: (a) ionization correction, and (b) relative metallicity)
- $A=3000 \text{ cm}^2 R=1000 @ 1 \text{ keV}$:
 - Detects hundred(s) of WHIM systems along ~ 100 sightlines ($F_{0.5-2} > 0.1-0.5 \text{ mCrab}$)
 - Measures $dN/dzdN_{\text{OVII}}$ and Ω_b at better than *few* %
 - Ionization correction and metallicity estimates for the strongest OVII systems ($\text{NOVII} > \sim 10^{15} \text{ cm}^{-2}$)
- $A=3000 \text{ cm}^2 R>=3000 @ 1 \text{ keV}$ ($50 \text{ km/s} <=> \text{O thermal velocity}$)
 - Accurate Ion column density measurements for 80 % of H-like and He-like C, N, O and Ne ==> Ionization correction and relative metallicity ==> accurate Ω_b estimates
 - Accurate temperature estimates ==> measuring internal turbulence and local bulk motion for C, N and O
 - Minimizes confusion due to overlapping lines from different systems
 - Starts resolving phases